Land Use in LCA (Subject Editor: Llorenç Milà i Canals)

Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption

Part 1: Conceptual Analysis and Methodological Proposal *

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Preamble. The present paper is the first in a series of two. The paper addresses the conceptual aspects of modelling global agricultural land use for LCI. Based on the outlined concepts, the second paper presents a practical example of global land use modelling.

Abstract

Background, Aims and Scope. The actual land use consequences of crop consumption are not very well reflected in existing life cycle inventories. The state of the art is that such inventories typically include data from crop production in the country in which the crop is produced, and consequently the inventories do not necessarily consider the land ultimately affected in the systems being studied. The aims of this study are to analyse the mechanisms influencing the long-term land use consequences of changes in crop demand and to propose a methodological framework for identifying these consequences within a global scope.

Materials and Methods. The study refers to the principles of consequential LCA, which means that the consequences of changes in consumption are studied from a market-based perspective. In this context, the study addresses the feasibility of using economic modelling to identify ultimate land use consequences of crop consumption.

Results. Based on the current market trend for crops and an analysis of basic mechanisms in crop production, concepts for modelling how crop consumption affects the global agricultural area and the intensity of crop production are suggested. It is demonstrated how the assumptions concerning drivers for technological development have a profound influence on identification of the marginal response to crop consumption, and how the geographical location of crop consumption also influences the composition of the marginal production response in terms of cropland expansion and intensification.

Discussion. Crop prices have been falling at a global scale and are projected to decline further. At the same time, crop yields per hectare are continuously increasing. This indicates that drivers other than crop demand have a strong influence on technological development in crop production.

Conclusions. Economic modelling in combination with geographical information and agricultural statistics can be used to estimate long-term land use consequences of changes in crop consumption. The GTAP Model is a suitable tool although it requires implementation of land supply curves, adjustment of elasticities to reflect long-term changes, and possibly establishment of a link between crop demand and technological development. Through this approach, life cycle inventories for crops reflecting the actual land use consequences of consumption can be established.

Recommendations and Perspectives. Further work (based on the methodological framework in this study) will address the practical modelling of land use changes induced by crop consumption in different regions with the purpose of including this in LCI.

Keywords: Agriculture; consequential LCA; crops; GTAP (Global Trade Analysis Project); land use; marginal production

Introduction

For centuries, mankind has expanded the global agricultural area (pastures and croplands) in order to grow crops and raise livestock. As **Fig. 1** shows, this trend continued up to

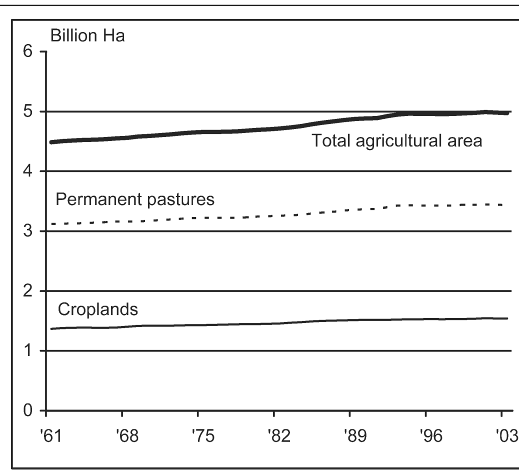

Fig. 1: Global development of croplands, permanent pasture and total agricultural area from 1961 to 2003. FAOSTAT (2007)

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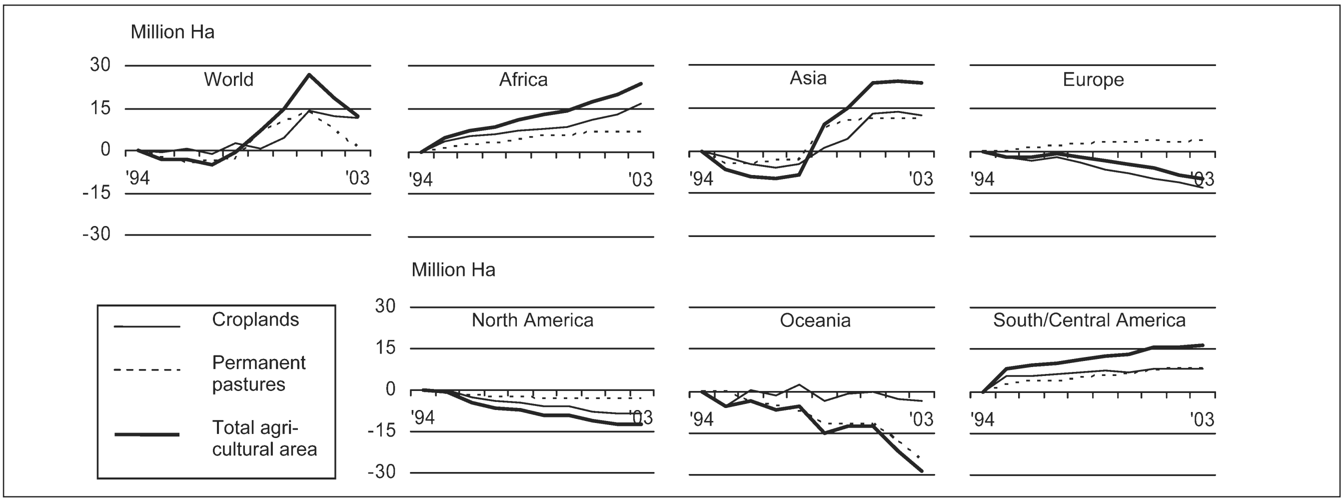

Fig. 2: Regional development of croplands, permanent pastures and total agricultural area from 1994 to 2003. Reference year: 1994. FAOSTAT (2007)

the middle of the 1990s. Since then, the increase has been very modest. However, as shown in **Fig. 2**, different regional trends in agricultural areas can be observed. One of several factors influencing these trends is crop demand. Any purchase and consumption of crops will influence the global agricultural area, and these land use effects should be included in LCA. This is generally acknowledged, but there is still no consensus on how to do it. Some research has focused on land use impact assessment (Lindeijer 2000, Mila i Canals et al. 2007), but few have looked at its precondition, namely the identification of the land actually affected in the systems under study. As demonstrated by Kløverpris (2006), this element is crucial for the validity and credibility of an LCA in which land use aspects are involved. In such studies, inventory data from the *direct crop suppliers* (farmers producing the crops used in the relevant life cycle) is often used. However, this does not necessarily reflect the actual consequences of crop consumption in markets involving international trade as crop markets typically do. Increased crop demand leads to increased production and, if production cannot be increased in the country or region in question, production will be increased elsewhere. The question is where and how. The location in which crop production is increased and the ways in which it is increased (intensification or cropland expansion) are decisive for the environmental impacts of crop consumption.

Weidema (2003) suggests a general approach to identifying the marginal/most sensitive supplier, suggesting that the supplier or technology most sensitive to changes in demand in the long run will be the one with the lowest (long-term) production costs (under certain conditions). This general principle, however, needs more detailed understanding for crop production, which is characterised by literally millions of suppliers and a sliding transition between low-tech and high-tech agriculture. Furthermore, production costs do not include transport costs and possible tariff costs, which also affect the competitiveness of crop suppliers.

The purpose of this paper is to present a conceptual analysis of crop production and the mechanisms determining land use consequences of changes in the demand for specific crops. Based on this analysis, a method will be proposed to quantify these land use changes and determine their geographical location in order to include them in life cycle inventories for crop consumption.

The term *marginal crop production* will be used to designate changes in crop production resulting merely from changes in crop demand. In other words, marginal crop production is the marginal production response to consumption of a given crop.

The agricultural term *marginal land* is commonly used to describe the farm land being brought into production last and abandoned first because it is likely to give a poor return. In this sense, marginal crop production is not so different (except for a larger geographical scale) because it is the last amount of crops produced or the crops that were not produced due to decreasing demand.

As the alternative to crop consumption is no consumption (or consumption of something else), the decision to consume crops will, seen in isolation, increase the demand for crops. The term *crop consumption* will therefore be used synonymously with *increased demand for crops* throughout this paper.

1 Scope

The study considers all types of crop consumption except those of a magnitude which is large enough to change the structure and trend of the global crop market.

Geographical scope: Major crops such as wheat, maize and rice are traded on the global market. Changes in crop demand may therefore, in principle, have consequences anywhere in the world and a global scope is applied in the study.

Temporal scope: The study addresses long-term land use consequences of crop consumption taking place in the existing market for crops. However, it is assumed that the full effects of crop consumption occur instantaneously under the conditions of the present market mechanisms. This is a common assumption in LCA, although the full effect will be revealed over a period of time.

Technological scope: In accordance with the assumption of instantaneous adaptation to changes in crop demand, production with present agricultural technology is assumed (unless demand affects the technological development, see Section 2.8).

Methodological scope: The study builds on the consequential approach to system modelling in LCA, which is generally characterised by the analysis of consequences caused by a given change or decision (Wenzel 1998, Ekvall and Weidema 2004). In consequential LCA, marginal data is used in the life cycle inventory (Weidema et al. 1999) and system expansion is used in the event of co-product and reuse/recycling/recovery issues. As discussed in Mila i Canals et al. (2006), the consequential approach to land use system modelling solves the long-known problem of transformation allocation between subsequent land use activities (see e.g. Lindeijer et al. 2002) by considering the market situation of crop production.

2 Analysis of the Mechanisms Determining Land Use Consequences of Marginal Crop Production

To determine the marginal response to crop consumption, it is necessary to identify and analyse the mechanisms that influence the consequences of changes in crop demand.

2.1 Long-term supply elasticity of crops

In competitive markets with no constraints on production factors, long-term prices are not determined by demand but by the long-term production costs, implying perfectly elastic supply (Weidema 2003). This means that, in the long run, an increased demand will be met by an equal increase in production (**Fig. 3**). This assumption is often implicitly used in LCA but the question is whether it is valid for crops. According to Abler (2003), intermediate inputs to crop production (fertilisers, pesticides, etc.) are presumed to be unconstrained and Bruinsma (2002) states that the world is not approaching shortages of suitable agricultural land at the global level (despite regional shortages). Apparently, this implies that the global supply of crops is perfectly elastic. However, that is not necessarily the case as differences in land fertility may cause differences in production costs. Furthermore, transportation and trade costs are also affecting crop prices (see Section 2.9).

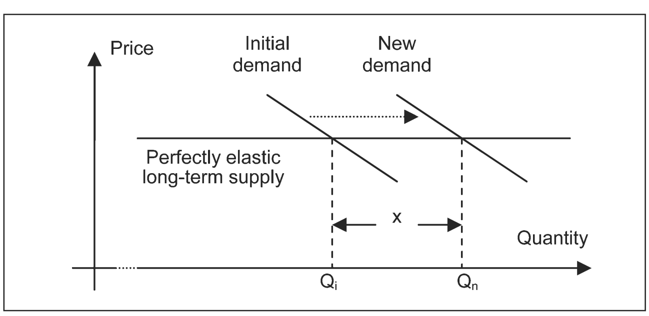

Fig. 3: General illustration of a perfectly elastic long-term supply in which the price equals the long-term production costs. If the demand increases by x, the demand curve will move to the right (as indicated by the dashed arrow) and the increase in the quantity produced will also be x ($Q_n - Q_i$)

2.2 Basic mechanisms in crop production

Global crop production is increasing due to population growth, increasing incomes in large Asian economies, and increased application of crops for non-food purposes, especially biofuels (OECD/FAO 2006). Basically, there are three main mechanisms to increase the production of a specific crop:

1. *Displacement* of other crops
2. *Expansion* of croplands
3. *Intensification* of existing production

Although these mechanisms have all been expressed as ways to *increase* production, the inverse of displacement, expansion and intensification can, in principle, be used for the opposite purpose.

2.3 Relationship between crop consumption and land use changes

In a growing global market, crop consumption will further increase the demand for crops. In the short term, increased demand for a specific crop *i* will lead to increased prices. Suppliers (farmers) will thus have incentives to produce more of crop *i*. They can do this by displacement, expansion and/or intensification. Suppliers closer to the consumer will benefit more due to lower transportation costs. Likewise, suppliers with easy access to the market in terms of low or no tariff payments will be more likely to cover the increased demand. These suppliers (and possibly also some in a less advantageous position) will respond to the increased demand for crop *i*. To the extent that displacement is used to cover this demand, the supply of other crops will decrease and, in the short term, prices will increase. This will give other farmers incentives to produce more of these crops (or substitutes). This mechanism is designated *replacement* (of the crops displaced to begin with). Besides expansion and intensification, replacement may also involve new displacement (and subsequent replacement) and, consequently, the effects of the initial crop consumption will trickle through the global agricultural system. This chain of events will continue until it reaches suppliers only responding with expansion and/or intensification (and no displacement). At this point, production and prices will stabilise and a new economic equilibrium will emerge. The land use change resulting from the initial consumption of crop *i* will be the sum of expansion that has taken place through the process.

2.4 Displacement

To the extent possible, displacement will occur whenever it becomes more profitable to produce one crop than others. This will happen when the demand for specific crops changes. However, farmers cannot choose freely to produce one crop rather than another since several constraints apply. These are constituted by climate conditions, soil properties and crop rotation schemes. Furthermore, farmers need to grow several crops in order to limit economic consequences of possible harvest failure. In some regions of the world, displacement may be the only option for responding to changes in demand. If farmers are not able to expand or intensify production (due to regulations or other constraints), they

can only adjust to changing market conditions by planting the most profitable mix of crops. In such cases, the marginal land use consequences of crop consumption will be found in other regions due to the displacement-replacement mechanism discussed above.

2.5 Expansion of croplands

Expansion of croplands is an intuitively obvious mechanism for increasing crop production. This process typically takes place at the expense of nature, but may also occur on land already transformed, e.g. due to timber production (Lambin and Geist 2003). Expansion is therefore a special case of *transformation*, which is the term generally used in LCA for conversion of one type of land use to another. With regard to marginal crop production, this study defines expansion as a process relative to the ongoing trend in cropland area. Expansion can, therefore, in principle, also be constituted by delayed release of croplands (**Fig. 4**).

According to FAOSTAT (2007), global croplands have increased by approximately 13% (more than 170 million hectares) since 1961 (see Fig. 1), and in this study increased crop demand is assumed to be the main driver. Interestingly, croplands in Europe and North America have been slightly decreasing in recent years despite increasing global crop demand (see Fig. 2). There may be several explanations for this, including subsidised afforestation, expansion of infrastructure and cities, more demand for recreational areas, and (not least) changes in agricultural policies. Besides that, the options for cropland expansion in parts of Europe (and some other regions) are limited simply because most suitable land has already been brought into production during centuries of agricultural expansion. This means that countries in such regions face physical (and possibly also regulatory) cropland constraints. Meanwhile, yield increases per hectare (intensification) continuously reduce the need for cropland expansion, but apparently not enough to prevent it from happening in Africa, South/Central America and, to some extent, Asia (see Fig. 2).

2.6 Intensification of existing production

In the middle of the twentieth century, intensive agricultural research was funded by private foundations and national governments because of threatening food shortages. This led to dramatic increases in annual crop yields and became known as the green revolution (IFPRI 2002). Since 1961, world food production has doubled (Ramankutty et al. 2006), while the global agricultural area has only increased by roughly 10% (see Fig. 1), meaning that the remaining 90% or so of the increased food production came from intensified production. This emphasises the importance of intensification and the need to consider it in the analysis of marginal crop production. Intensification has been divided into two subgroups, namely *optimisation of production* and *technological development*.

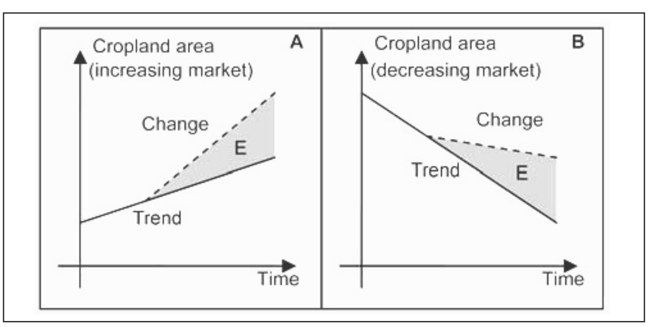

Fig. 4: Cropland expansion (E) derived from marginal crop production can either take the form of accelerated expansion in an increasing market (A) or delayed release of croplands in a decreasing market (B). In both situations, the expansion is the difference between the existing trend (business as usual) and the change resulting from the increased demand for crops

2.6.1 Optimisation of production

Farmers can intensify crop production by increasing -

- Fertiliser application
- Pesticide application
- Irrigation level
- Cropping intensity[1]

However, these options are subject to diminishing returns: the higher the level of fertiliser, pesticide and/or water application on a given field, the lower the increase in yield per unit of input (**Fig. 5A**). The reason why cropping intensity is also subject to diminishing returns is that increased cropping intensity requires increased inputs of fertilisers, pesticides and water.

Due to the diminishing returns, there is an optimum level for the four optimisation options. The optimum is determined by the largest difference between the value of production (yield multiplied by crop price) and the production costs, which are linearly related to the input level (**Fig. 5B**). If the prices of crops or inputs change, farmers will adjust the application levels. Therefore, agricultural (price) support leads to intensified production. However, regulatory constraints may apply to application of fertilisers, pesticides and irrigation. For example, many EU countries have imposed a limit on yearly organic N fertilisation of 170 kg/ha (European Commission 2002). Typically, the use of pesticides is also regulated because of their toxicological properties. Furthermore, irrigation restrictions may apply in some regions, especially where water is scarce. Finally, there is an upper limit to cropping intensity set by climatic conditions.

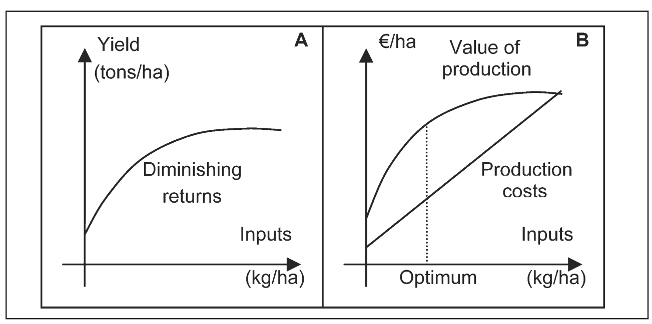

Fig. 5: Relationship between inputs and yield per hectare at a given technological stage (A) and the implications for profit optimisation (B). The optimum level of inputs is characterised by the largest difference between production costs and value of production (yield multiplied by crop price)

[1] The ratio between harvested area per year and the area of arable land (Bruinsma 2002).

2.6.2 Technological development

Intensification can also be achieved through technological development to essentially improve

- Mechanical aids
- Crop strains
- Agricultural practices

As opposed to the optimisation mechanisms, which can also be used to lower yields per hectare in the case of decreasing demand, the technological development within the three areas mentioned above will always lead to increased annual crop yields per hectare simply because technological improvements are not discarded in case of falling prices.

Adoption of technological improvements occurs automatically as long as they offer lower production costs. This can be explained by the theory of *the agricultural treadmill* put forward by Cochrane (1958): a small group of innovative farmers will adopt new technologies early and, consequently, increase their production capacity and market share. Since they only constitute a small fraction of the suppliers, prices will remain relatively unchanged. However, when the larger group of less innovative farmers realise the benefits of the new technology, their adoption will cause a significant supply increase, resulting in falling prices. The non-adopters will be the losers because their production costs remain the same while prices fall (Gabre-Madhin et al. 2002). The agricultural treadmill demonstrates how new technology is adopted regardless of demand changes.

Control of technological development is beyond farmers. Agricultural machinery is developed by private companies, which is also the case for improved crop strains, although some of this development takes place in public research institutions (Andersen 2006). Development of improved agricultural practices is an international research field primarily based in public research institutions (Andersen 2006).

Drivers of technological development: The main driver for the development of better mechanical aids for crop production is assumed to be internal competition between suppliers of agricultural machinery. However, it cannot be ruled out that increased crop demand will also influence the speed of technological development within this field. The general drivers for the development of better crop strains are assumed to be crop demand and internal competition between companies developing and selling seeds. The demand for crops will influence the research priorities within these companies. More resources will be allocated to the crops in high demand because these are being sold in large quantities. Furthermore, public funds may be allocated to this field of research in case of existing or perceived future societal food shortages. This can also be considered a type of demand. Meanwhile, internal competition between seed providers will also drive the development of better crop strains. The general drivers for development of better agricultural practices will mainly be political decisions since this is mainly a public research field. This means that societal needs may also influence this development just as for crop strain development. In summary, crop demand has a certain influence on technological development, but other factors such as internal competition between commercial developers also play a role.

2.6.3 Interrelation between optimisation and technological development

At a given technological stage (see Fig. 5A), optimisation will be determined by two factors, namely crop prices (determining the value of production) and the prices of fertilisers, pesticides, irrigation and other inputs determining production costs (see Fig. 5B). However, seen over a period of time, a third factor will influence optimisation, namely technological development, which will move the curve in Fig. 5A upwards and tend to stretch it out. This means that the crop yield per hectare related to a given input level will increase over time, while crop prices will decrease due to the lower costs per unit of output (see Section 2.1). The changes in crop prices and yield will affect the value of production (in opposite directions), and consequently the optimum application of inputs (see Fig. 5B). This illustrates how technological development has a profound impact on optimisation.

2.7 Composition of marginal crop production

Based on the analysis of displacement, expansion and intensification, a mathematical description of marginal crop production (demand driven by definition) can be derived. As displacement is only an intermediate process (see Section 2.4), changes in global crop production will ultimately stem from expansion and intensification. As discussed previously, cropland expansion is assumed to be driven by demand, whereas intensification may be partly driven by other factors. This means that the continuous increase in global crop production (ΔQ), which has been observed over several decades, can be divided into three parts (**Eq. 1**).

$$\Delta Q = \Delta Q_A + \Delta Q_I = \Delta Q_A + \Delta Q_{I,d} + \Delta Q_{I,o} \tag{1}$$

where
ΔQ_A is the change in production caused by change in cropland area
ΔQ_I is the change in production caused by change in intensity
$\Delta Q_{I,d}$ is the change in production caused by change in intensity driven by demand
$\Delta Q_{I,o}$ is the change in production caused by change in intensity driven by factors other than demand

Changes in crop production can also be expressed in terms of area and yield per hectare:

$$\Delta Q_A = Y \cdot \Delta A \tag{2}$$
$$\Delta Q_I = \Delta Y\,(A + \Delta A) \tag{3}$$

where
Y is the initial average crop yield per hectare
ΔA is the change in cropland area
ΔY is the change in average crop yield per hectare
A is the initial cropland area

If a is the fraction of intensification driven by demand, marginal crop production (ΔQ_m) can be described as

$$\begin{aligned}\Delta Q_m &= \Delta Q_A + \Delta Q_{I,d} = \Delta Q_A + a \cdot \Delta Q_I \\ &= Y \cdot \Delta A + a \cdot \Delta Y\,(A + \Delta A)\end{aligned} \tag{4}$$

2.8 Significance of the relationship between demand and technological development

It is difficult to estimate the fraction of intensification derived solely from increased demand (a in **Eq. 4**). However, the significance of the relationship between demand and technological development with regard to marginal crop production can be demonstrated on the assumption of a perfectly elastic (long-term) supply of crops. This implies a fixed price at a given technological stage (see Fig. 3), ignoring the influence of transportation costs and possible tariffs related to the movement of crops (see Section 2.9). Under these conditions, only technological development will influence optimisation because it determines yield per unit of input (see Fig. 5) and, consequently, crop prices (see Section 2.1). In other words, intensification becomes synonymous with technological development because the latter inherently determines optimisation (still assuming perfectly elastic supply and costless movement of crops). Accordingly, a (in **Eq. 4**) becomes synonymous with the fraction of technological development driven by demand. The significance of the relationship between demand and technological development can therefore be analysed by assuming technological development to be fully driven by demand ($a = 1$) and completely driven by other factors ($a = 0$) respectively.

2.8.1 Technological development fully driven by demand

On the assumptions described in Section 2.8 and the additional assumption of technological development being fully driven by crop demand, no yield increases per hectare will be observed at a constant crop demand (conflicting with the theory of the agricultural treadmill). On the other hand, any increase in crop demand will lead to technological development and, consequently, higher yields per hectare. As no production increase occurs due to factors other than demand, marginal production becomes, by definition, synonymous with the total increase in production ($\Delta Q_m = \Delta Q = \Delta Q_A + \Delta Q_I$).

2.8.2 Technological development completely driven by factors other than demand

If technological development is assumed to be driven completely by factors other than crop demand, changes in crop demand will not affect the rate of crop yield increases per hectare (intensification) on the assumptions described in Section 2.8. This means that marginal crop production will only come from cropland expansion ($\Delta Q_m = \Delta Q_A$), which may partly be constituted by delayed release of cropland for other purposes (see Fig. 4).

2.9 Significance of the geographical location of crop consumption

As shown above, the relationship between technological development and crop demand has important implications for the composition of marginal crop production. The same is true for the geographical location of crop consumption (the physical origin of demand). The reason is that, besides production costs, the crop price paid by the buyer also includes transportation and possible trade costs in the form of tariffs. Therefore, it may sometimes be more profitable to pay local farmers (possibly without options for expansion) to intensify production (through the use of fertilisers, pesticides and/or irrigation) rather than buying crops from distant suppliers with lower production costs. This means that, even if technological development is considered to be completely unrelated to crop demand (see Section 2.8.2), intensification may still contribute to marginal crop production. This is because the price increases related to transportation and trade influence optimisation (see Fig. 5). Be aware that this price increase is not related to production costs. Even if all production factors in crop production are unconstrained (see Section 2.1), the supply of crops in a given location will not necessarily be perfectly elastic (fixed price in the long run at a given technological stage) because of the transport and trade issues. Increased crop demand will therefore lead to higher prices in areas with constraints on croplands and/or intensification options.

Some countries have removed or reduced the trade barriers between them by forming trade agreements or trade blocs of varying economic integration. This means that crops will flow more freely between these nations. Furthermore, some countries and trade blocs provide preferential access to their markets for developing countries. For example, the EU forms a preferential trading area for the African, Caribbean and Pacific countries and provides duty-free access to all products except weapons (plus sugar and rice up to 2009) from the Least Developed Countries (European Council 2001). These different trade arrangements influence crop flows in the market and may cause neighbouring countries to choose completely different crop suppliers simply because they belong to different trade blocs. Again, this illustrates why the geographical location of crop consumption influences the composition of marginal crop production.

3 Method Proposal for Identification of Land Use Consequences related to Marginal Crop Production

Based on the conceptual outline and analysis presented in Section 2, a proposal for an operational method for identification of land use changes related to marginal crop production is presented in this section.

3.1 Economic modelling of changes in crop demand

Some of the issues related to identification of marginal crop production can be handled by economic models developed to simulate the economic mechanisms of society. Jensen and Andersen (2003) have used a partial equilibrium (PE) model of the Danish agricultural sector to identify marginal suppliers of various agricultural products within the country. However, they assumed a fixed national area of croplands and did not consider displaced crops or import/export effects. To include these aspects, a global model is required with a sufficient number of regions and agricultural sectors. In van Meijl et al. (2006), three global PE models considering the mobility of land in and out of agricultural production are discussed, namely the FAO World Food Model, the FAPRI Model, and the Penn State Trade Model. Either of these models may be suitable for identification of marginal crop production although a disadvantage of PE models is that they do not take into account the interaction between the agricultural sectors and the remaining part of the world economy.

The Global Trade Analysis Project (GTAP) has developed a general equilibrium model in agreement with the principles of neoclassical economic theory. GTAP also maintains a database representing the global economy (87 regions with 57 sectors each). Primary production factors (capital, labour and land) are constrained in the model, and the interaction between sectors and regions is based on economic input-output databases, elasticities of supply and demand (empirically estimated or calibrated by the model), international trade regulations, and trade agreements (bilateral and multilateral). The economic consequences of a change (in demand, supply, policy, etc.) can be studied by introducing a so-called 'shock', e.g. a region-specific change in crop demand. The result is a new economic equilibrium with all changes expressed in relative terms. For further details, see Hertel (1997) or Klijn and Vullings (2005).

The fact that the GTAP Model reflects the entire global economy makes it well suited for the analysis of global consequences of changes in crop demand. The inclusion of trade agreements and regulations as well as a global transport sector reflecting the costs of transportation makes it possible to include geographical dependency in the analysis of changes in crop demand. Furthermore, the standard GTAP Model includes eight crop sectors and four livestock sectors, which are all using land as a primary production factor. Due to the elasticities incorporated in the model, it is possible to study the interaction between the different agricultural sectors when the demand in one of them is changed. Furthermore, it is also possible to study effects in other sectors.

3.1.1 Applying the GTAP Model to land use LCI modelling

Although the GTAP Model offers advantages for the establishment of land use inventory data for marginal crop production, the standard version also suffers from some weaknesses in this respect. However, most of these problems can be solved by modification of the model or informed interpretation of the results.

Land supply: The availability (supply) of land is constant in the standard GTAP Model. This means that shocking the demand for a specific group of crops will only result in displacement and intensification. However, van Meijl et al. (2006) have proposed the integration of so-called land supply curves in the GTAP Model, which will allow the use of agricultural land to be determined by the model. Expansion of the agricultural area can thus be estimated. Meanwhile, the construction of national or regional land supply curves requires data on the available amount of unutilised cultivable land (see Section 3.2).

Inputs to crop production: The GTAP Model mainly builds on economic theory and not so much on biophysical cause-effect mechanisms. For example, primary production factors (capital, labour and land) can substitute for one another, but intermediate inputs to production of goods are locked in a fixed nesting structure. This means that the proportions between intermediate inputs are constant. In other words, crop production cannot be optimised by adjusting the application of fertilisers alone, but only by adjusting all inputs equally. Bear in mind that land is considered a primary production factor and, consequently, it is not subject to the fixed nesting structure. This means that the model can calculate whether, and to what extent, expansion is more profitable than intensification (if the land supply curves mentioned above, or similar mechanisms, are implemented).

Time perspective and elasticities: The elasticities in the GTAP database do not necessarily reflect the long-term perspective typically applied in LCA. This data should therefore be adjusted. In particular, the so-called Armington elasticities expressing the inertia of changing trade patterns should be changed in order to allow for a full adjustment to the studied changes in crop demand.

Technological development: In the standard GTAP Model, the technological stage is assumed to be fixed. However, technological development can be incorporated either as an independent variable (determined outside the model) or as a function of another variable, e.g. crop prices. This decision depends on the assumption regarding the relationship between crop demand and technological development (see Section 2.8).

Conversion of relative changes to quantities: The fact that the GTAP Model expresses results as relative changes means that a conversion of the results is necessary to provide them in physical units such as mass of production and area of agricultural land use for LCI. This is possible using data from FAOSTAT (2007), but it requires a grouping of the FAOSTAT crops corresponding to the GTAP crop sectors.

Level of detail: The GTAP Model is quite coarse, which means that it does not contain detailed information about specific countries. For example, region-specific or country-specific limits on fertiliser application are not (by default) incorporated in the model. Such information must be included as ad hoc adjustments to the model or, alternatively, must be accounted for in the interpretation of the GTAP results when the composition of marginal crop production is analysed.

3.2 Utilising geographical information about land use and land use changes

Without the integration of the mentioned land supply curves (or a similar mechanism) in economic modelling, it is not possible to include the expansion aspect of marginal crop production in the modelling. As the construction of land supply curves is dependent on quantitative data on unutilised cultivable land, geographical information becomes vital to the assessment. Furthermore, qualitative information about current land use changes can be used to validate and supplement the results from the economic modelling. A consistency check can then be made to see if land use changes are actually taking place in the regions where cropland expansion is predicted to occur by the economic modelling. Information on current land use changes can also be used to identify the biotopes transformed in the regions affected. Finally, other types of information about current and future land use changes can be used. For instance, Bruinsma (2002) states that more than 80% of the future expansion in arable area is expected to take place in sub-Saharan Africa and Latin America, which conforms well with Fig. 2.

4 Results

This study has identified the main aspects of importance for LCI modelling of land use changes induced by crop consumption and has proposed a framework in which these complex issues can be handled simultaneously, namely economic modelling combined with geographical information. Depending on choices of assumptions regarding long-term supply elasticity and drivers for technological development, the result will come out as production changes in a number of regions in which some production will derive from intensification and some from expansion. The latter will involve transformation of natural areas, which can be quantified via data from FAOSTAT (2007). In other words, the results will provide an estimate of the actual land use changes induced by crop consumption. This information can be included in life cycle inventories – thereby providing the precondition for land use impact assessment.

5 Discussion

In the considerations regarding crop demand and technological development (see Section 2.8), the development in crop prices might contain useful information about the relationship between the two. As discussed previously, agricultural production has been intensified substantially since the 1960s. In the meantime, producer prices for crops have been falling on a global scale (Gabre-Madhin et al. 2002). This might indicate that technological development is driven by factors other than demand since price increases cannot explain the intensification. However, it must be kept in mind that the EU, the USA and others have paid considerable subsidies to their farmers for several decades. This has given these farmers incentives to intensify production (by use of fertilisers, pesticides and irrigation), and it has enabled them to sell their crops at a low price. In other words, technological development is not the only factor that has influenced producer prices in recent decades. However, it is not likely that agricultural support in itself can sustain a continuous decrease in producer prices unless the support is gradually increased, which is not the case nowadays. Nevertheless, real prices for agricultural commodities will continue to fall in the near-term future (OECD/FAO 2005). This is because the mechanisms strengthening supply, which are mainly productivity gains (technological development), seem to be stronger than the mechanisms strengthening demand, e.g. income and population growth (see **Fig. 6** for a conceptual illustration). It does, therefore, indeed seem that technological development in crop production is driven by other factors than crop demand, e.g. internal competition between developers of new crop strains and mechanical aids (see Section 2.6.2). It is also worth noticing that crop yields per hectare are generally projected to increase worldwide within the next 10 years (FAPRI 2006) despite the falling prices. Still, it cannot be ruled out that increased demand for crops will result in additional technological development in crop production, although this influence might be small compared to that of internal competition between suppliers of mechanical aids and seeds.

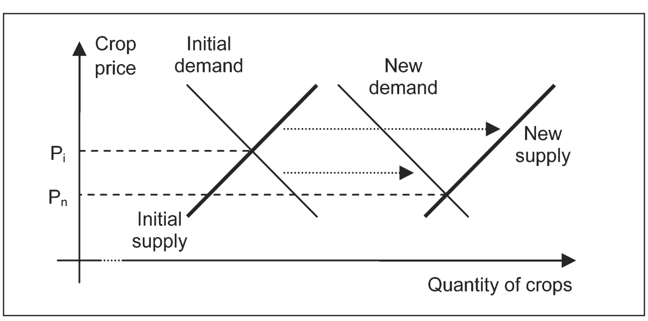

Fig. 6: Illustration of decreasing crop prices. Since the supply curve moves further to the right than the demand curve (movement indicated by dashed arrows), the new crop price (P_n) is lower than the initial crop price (P_i)

In agreement with the purpose of the present paper, the main focus has been on land use changes, i.e. the area(s) transformed (land type and geographical location) as a result of crop consumption in a given region. Meanwhile, the other side of marginal crop production, namely demand-driven intensification (optimisation) must also be accounted for in LCA. Although this lies beyond the scope of the present paper, a brief discussion of the issue follows: Part of the results from a GTAP simulation is the relative changes in intermediate inputs to sectors. For instance, if the demand for wheat increases by x tons in a given region, the intermediate inputs to the oilseed sector in a neighbouring region may increase by 1 percent due to the displacement-replacement mechanisms. The intermediate inputs include fertilisers, pesticides, fuel, water and other inputs to be listed in the LCI. A disadvantage of the GTAP Model is that some of these inputs (e.g. fertilisers and pesticides) belong to the same sector (and consequently cannot be separated out). Therefore, it is necessary to couple the GTAP results with more fine grained information on inputs to crop production, e.g. national agricultural statistics. If such information is not available for individual crop sectors in the relevant regions, it might be necessary to calculate a weighted average of the change in intermediate inputs to all crop sectors in a region. When the initial inputs to crop production are known and the relative changes in inputs are given by the GTAP Model, it is possible to calculate the increased inputs used for intensification and list them in the LCI.

6 Conclusions

Increased production of specific crops can be achieved by displacement, expansion and intensification. Displacement will lead to replacement and, ultimately, the marginal response to crop consumption will be a combination of expansion and intensification. The latter can be achieved through optimisation (application of fertilisers, pesticides and irrigation) or technological development (improved mechanical aids, crop strains and agricultural practices). Assumptions concerning drivers for technological development have important implications for identifying the composition of marginal crop production. Furthermore, the geographical origin of crop consumption influences the marginal production response since transportation and trade costs might make intensification more attractive than imports in regions without possibilities for cropland expansion. The marginal response to crop consumption, including geographical dependency, can be estimated using economic model-

ling. In the GTAP Model, results will come out as relative changes in regional production and agricultural areas. These results can be converted to physical units using agricultural statistics, and their validity can be tested by comparing to geographical information on current land use changes. This will enable impact assessment of land use in LCA reflecting the actual consequences of crop consumption. Decision makers will thereby be able to consider the environmental impacts of the land use changes in other regions caused by the decisions taken in their own region.

7 Recommendations and Perspectives

Further work will address the practical modelling of long-term marginal responses to consumption of different crops in different regions of the world using the GTAP Model. Furthermore, an analysis will be made of the extent to which the magnitude of consumption influences the result in terms of the ratio of intensification to expansion as well as the distribution of regions affected. The findings of this work will be published in Kløverpris et al. (in prep).

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